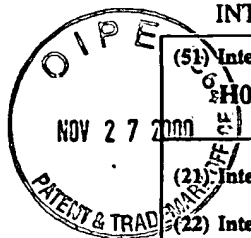




INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification⁶:

H01G 7/02, H04R 31/00

A1

(11) International Publication Number:

WO 97/39464

(43) International Publication Date:

23 October 1997 (23.10.97)

(21) International Application Number: PCT/US97/06554

(22) International Filing Date:

18 April 1997 (18.04.97)

(30) Priority Data:

60/016,056

18 April 1996 (18.04.96)

US

(71) Applicant: CALIFORNIA INSTITUTE OF TECHNOLOGY
[US/US]; 1201 East California Boulevard, Pasadena, CA
91125 (US).(72) Inventors: TAI, Yu-Chong; California Institute of Technol-
ogy, Electrical Engineering, 136-93, Pasadena, CA 91125
(US). HSU, Tseng-Yang; California Institute of Technol-
ogy, Electrical Engineering, 136-93, Pasadena, CA 91125
(US). HSIEH, Wen, H.; California Institute of Technology,
Electrical Engineering, 136-93, Pasadena, CA 91125 (US).(74) Agent: HARRIS, Scott, C.; Fish & Richardson P.C., Suite
1400, 4225 Executive Square, La Jolla, CA 92037 (US).(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR,
BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE,
HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS,
LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL,
PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA,
UG, UZ, VN, ARIPO patent (GH, KE, LS, MW, SD, SZ,
UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ,
TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR,
GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF,
BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

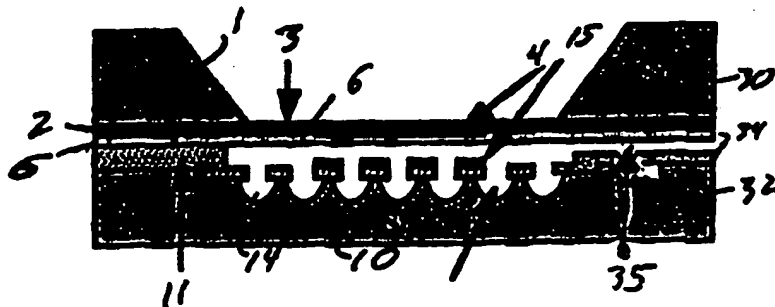
Published

*With international search report.**Before the expiration of the time limit for amending the
claims and to be republished in the event of the receipt of
amendments.*

(54) Title: THIN FILM ELECTRET MICROPHONE

(57) Abstract

A method of making an electret microphone comprising juxtaposing a microphone membrane unit (30) and a microphone back plate (32), at least one of which includes a micro-machined electret layer (6) formed on a support structure, thereby producing a highly reliable, inexpensive microphone. Thermal annealing is used to stabilize the implanted charge.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

THIN FILM ELECTRET MICROPHONE

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

The U.S. Government has certain rights in this invention pursuant to Grant No. ECS-9157844 awarded by the National Science Foundation.

5 BACKGROUND OF THE INVENTION

1. *Field of the Invention*

This invention relates to electret microphones, and more particularly to miniature electret microphones and methods for manufacturing miniature electret microphones.

2. *Description of Related Art*

10 An electret is a dielectric that produces a permanent external electric field which results from permanent ordering of molecular dipoles or from stable uncompensated surface or space charge. Electrets have been the subject of study for their charge storage characteristics as well as for their application in a wide variety of devices such as acoustic transducers (including, for example, hearing aids), electrographic devices, and photocopy
15 machines.

A number of electret microphone designs exist. However, small, high quality electret microphones tend to be quite expensive. Therefore, a need exists for small, high quality, inexpensive electrets, particularly electret microphones. The present invention meets these needs.

SUMMARY OF THE INVENTION

The present invention uses micro-machining technology to fabricate a small, inexpensive, high quality electret on a support surface, and further uses micro-machining technology to fabricate a small, inexpensive, high quality, self-powered electret sound transducer, preferably in the form of a microphone. Each microphone is manufactured as a two-piece unit, comprising a microphone membrane unit and a microphone back plate, at least one of which includes an electret formed by micro-machining technology. When juxtaposed, the two units form a highly reliable, inexpensive microphone that can produce a signal without the need for external biasing, thereby reducing system volume and complexity.

10 In the preferred embodiment, the electret material used is a thin film of spin-on polytetrafluoroethylene (PTFE). An electron gun preferably is used for charge implantation. The electret has a saturated charged density in the range of about 2×10^{-5} C/m² to about 8×10^{-4} C/m². Thermal annealing is used to stabilize the implanted charge.

15 Two prototype micro-machined electret microphones have been fabricated and tested. An open circuit sensitivity of about 0.5 mV/Pa has been achieved for a hybrid microphone package.

The details of the preferred embodiment of the present invention are set forth in the accompanying drawings and the description below. Once the details of the invention are known, numerous additional innovations and changes will become obvious to one skilled in the art.

20

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1A is a process flow chart for the electret microphone of a first embodiment of the present invention, showing fabrication stages for the microphone membrane.

5 FIGURE 1B is a process flow chart for the electret microphone of a first embodiment of the present invention, showing fabrication stages for the microphone back plate.

FIGURE 2A is a plan view of the completed microphone membrane of FIGURE 1A.

FIGURE 2B is a plan view of the completed microphone back plate of FIGURE 1B.

FIGURE 2C is a closeup view of a section of the completed microphone back plate of FIGURE 2B.

10 FIGURE 3 is a cross-sectional view of the completed hybrid electret microphone of a first embodiment of the present invention.

FIGURE 4 is a process flow chart for the electret microphone of a second embodiment of the present invention, showing fabrication stages for the microphone back plate.

15 FIGURE 5 is a diagram of a preferred back-light thyatron charge implantation system for make electret film in accordance with the present invention.

Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION OF THE INVENTION

Throughout this description, the preferred embodiment and examples shown should be considered as exemplars, rather than as limitations on the present invention.

Overview

5 In accordance with the invention, miniature (e.g., 3.5 mm × 3.5 mm) electret microphones are manufactured as a two-piece unit comprising a microphone membrane unit and a microphone back plate, at least one of which has an electret formed by micro-machining technology. When juxtaposed, the two units form a microphone that can produce a signal without the need for external biasing. However, the invention includes forming an electret
10 on a support surface for other desired uses.

In the preferred embodiment, the electret material used is a thin film of a spin-on form of polytetrafluoroethylene (PTFE). An electron gun, known as a pseudo-spark device, is used for charge implantation.

To demonstrate the self-powering capability of a Micro Electro-Mechanical Systems
15 (MEMS) compatible electret device, two different prototype micro-machined electret microphones have been fabricated and tested. Prototype A used a silicon back plate, and the prototype B used a glass back plate. Both microphones use the same diaphragm (membrane) chip. In these examples, the electret has a saturated charged density in the range of about 2×10^{-3} C/m² to about 8×10^{-4} C/m². An open circuit sensitivity of about 0.5
20 mV/Pa has been achieved for a hybrid microphone package.

Electret Microphone A

FIGURE 1A is a process flow chart for the electret microphone of a first embodiment of the present invention, showing fabrication stages for the microphone membrane. FIGURE

2A is a plan view of the completed microphone membrane of FIGURE 1A. The fabrication process for electret microphone A involves the following steps:

- 1) Fabrication of the microphone membrane begins with a silicon substrate 1 coated with about 1 μm thick, low stress, low pressure chemical vapor deposition (LPCVD) silicon nitride acting as a membrane layer 2. Other electrically insulating or semiconducting glass, ceramic, crystalline, or polycrystalline materials can be used as the substrate material. For example, the substrate material may be glass (see, *e.g.*, Electret Microphone #2 below), quartz, sapphire, *etc.*, all of which can be etched in many known ways. Other membrane layer materials (such as silicon dioxide) capable of being fabricated in a thin layer can be used, formed or deposited in various known ways.
- 2) The silicon nitride on the back side of the substrate 1 is then masked with photoresist, patterned, and etched (*e.g.*, with SF_6 plasma) in conventional fashion to form a back-etch window. The substrate 1 is then anisotropically back-etched to form a free-standing diaphragm 3 (about 3.5 mm \times 3.5 mm in the illustrated embodiment). The etchant may be, for example, potassium hydroxide (KOH), ethylene diamine pyrocatecol (EDP), or tetramethyl ammonium hydroxide (TMAH).
- 3) A membrane electrode 4 is then deposited on the front side of the diaphragm 3, preferably by evaporation of about a 2000Å thick layer of Cr/Au through a photoresist or physical mask. Other conductors may be used, such as aluminum or copper, and deposited in other fashions.
- 4) A dielectric film 5 is then spun on to a thickness of about 1 μm . The dielectric film 5 preferably comprises PTFE, most preferably Teflon® AF 1601S, a brand of Du Pont fluoropolymer. This material was chosen because it is available in

liquid form at room temperature, thus making it suitable for spin-on applications. This material also forms an extremely thin film (down to submicron thicknesses) which allows for an increase in the mechanical sensitivity of the microphone membrane, and it has excellent charge storage characteristics, good chemical resistance, low water absorption, and high temperature stability. However, other dielectric materials could be used, such as Mylar, FEP, other PTFE fluoropolymers, silicones, or Parylene.

In the prototype, a Teflon® AF dielectric film was prepared by spinning at about 2 krpm and baking at about 250°C for about 3 hours. With one application of liquid Teflon® AF followed by spinning, the resulting dielectric film was about 1 μm thick with a surface roughness of less than about 2000 Å across the substrate (microphone A). With two consecutive applications of liquid Teflon® AF, the resulting dielectric film was about 1.2 μm thick (microphone B). For time spans longer than usual processing times, the adhesion of the Teflon® film to different material surfaces (e.g., silicon, silicon dioxide, silicon nitride, copper, gold, chrome, etc.) is satisfactory in the presence of chemicals (e.g., water, photoresist developers, acetone, alcohol, HF, BHF, etc.) frequently used in MEMS fabrication. If desired, the film 5 can be patterned with, for example, oxygen plasma using a physical or photoresist mask.

5) Lastly, an electret 6 is formed by implanting electrons of about 10 keV energy into the dielectric film 5, preferably using a pseudo-spark electron gun. The electret 6 was then annealed in air at about 100°C for about 3 hours to stabilize the charge.

The pseudo-spark electron gun, described below, is preferred because it operates at room temperature, the electron beam energy can be easily varied from about 5 keV to about 30 keV, the beam size is large (about several millimeters in

diameter), it can deliver high electron doses (10^{-9} to 10^{-6} C), it has high throughput, and is low cost. However, other electron implantation methods may be used, such as a scanning electron beam, field emission electrode plate, corona charging, liquid contact, or thermal charging.

5 FIGURE 1B is a process flow chart for electret microphone A, showing fabrication stages for the microphone back plate. FIGURE 2B is a plan view of the completed microphone back plate of FIGURE 1B. FIGURE 2C is a closeup view of a section of the completed microphone back plate of FIGURE 2B. The fabrication process involves the following steps:

- 10 1) The back plate electrode is fabricated starting with a silicon substrate 10 coated with an electrically insulating layer 11, preferably comprising about 3 μm of thermal oxide. Both sides of the substrate 10 are shown coated with the insulating layer 11, but only one side (the side containing the electrode) need be coated. Other materials, such as silicon nitride, may be used for the electrical insulating
15 layer 11. Other electrically insulating or semiconducting glass, ceramic, crystalline, or polycrystalline materials can be used as the substrate 10 material.
- 20 2) Portions of the insulating layer 11 are masked and etched to the substrate 10 to form an etching window. The exposed substrate 10 is then etched through the etching window to form a recess 12. In the preferred embodiment, a timed KOH etch is used to create an approximately 3 μm recess 12 in the substrate 10. The window and recess 12 form the air gap of the capacitive electret microphone.
- 3) An electrically insulating layer 13 is then grown, filling the recess 12. The insulating layer 13 preferably comprises about 3 μm of thermal oxide.

- 4) The insulating layer 13 is then patterned to form an array of cavities 14 for reducing air streaming resistance during microphone operation. In the preferred embodiment, the cavity array is 40×40 , and is formed by anisotropic etching (e.g., by KOH) followed by isotropic etching (e.g., by hydrofluoric acid + nitric acid + acetic acid) through the patterned insulating layer 13. In the illustrated embodiment, each cavity has about a $30 \mu\text{m}$ diameter opening, and comprises a half-dome shaped hole about $80 \mu\text{m}$ in diameter and about $50 \mu\text{m}$ deep.
- 5) Lastly, a back plate electrode 15 is deposited on part of the insulating layer 13, preferably by evaporation of about a 2000\AA thick layer of Cr/Au through a physical mask. Other conductors may be used, such as aluminum or copper, and deposited in other fashions, such as thick film printing.

For electret microphone A, the fundamental resonant frequency of the microphone membrane with a Cr/Au membrane electrode 4 and a Teflon electret film 6 was measured using a laser Doppler vibrometer. The fundamental resonant frequency was found to be around 38 kHz.

FIGURE 3 is a cross-sectional view of the completed hybrid electret microphone A. The microphone membrane 30 and back plate 32 are shown juxtaposed such that the electret 6 is positioned approximately parallel to but spaced from the back plate electrode 15 by a gap 34. The microphone membrane 30 and back plate 32 may be mechanically clamped together, or bonded adhesively, chemically, or thermally. If desired, the completed microphone may be enclosed in a conductive structure to provide electromagnetic (EM) shielding. If the microphone membrane 30 and back plate 32 are hermetically sealed together in a vacuum chamber, the cavities 14 and the steps required for their formation may be omitted, since air streaming resistance would not pose a problem. Otherwise, a static pressure compensation hole 35 may be provided.

While the electret 6 is shown as being formed on the membrane 30, similar processing techniques can be used to form the electret 6 on the facing surface of the back plate 32, or on both the membrane 30 and the back plate 32.

To reduce stray capacitance, the total electrode area was designed so that it only covered a fraction of the area of the microphone membrane 30 and back plate 32. In the experimental microphone A prototype, only 2×2 mm electrodes were used to cover the center part of a 3.5×3.5 mm diaphragm 3 and a 4×4 mm perforated back plate 32. The fraction of the back plate area occupied by the cavity openings was 0.07 in this prototype. The streaming resistance, R_s , was calculated to be 0.03 Ns/m. The cut-off frequency ($f_c = 13.57 \sigma h / \{2\pi R_s\}$, where $\sigma = 100$ MPa is the diaphragm 3 stress and $h = 1 \mu\text{m}$ is the diaphragm 3 thickness) was calculated to be approximately 7.6 kHz.

The theoretical capacitance of microphone A was 7 pF with a 4.5 μm air gap, a 1 μm thick Teflon electret 6, and an electrode area of 4 mm². Using a Hewlett Packard 4192 LF Impedance Analyzer, the measured capacitance of the completed microphone A package was about 30 pF. The discrepancy in capacitance values can be attributed to stray capacitance between the electrodes and silicon substrates and between the two clamped silicon substrate halves of the microphone.

Microphone A was able to detect the sound from a loud human voice without the use of an amplifier. When the microphone was connected to an EG&G PARC model 113 Pre-amp (gain set at 1000) and was excited by a Bruel & Kjaer Type 4220 Pistonphone operating at 250 Hz and 123.9 dB (re. 20 μPa) amplitude, the oscilloscope displayed a 250 Hz, 190 mV peak-to-peak amplitude signal. The estimated open-circuit sensitivity of the microphone A is 0.3 mV/Pa. The open-circuit sensitivity of the microphone can also be estimated by calculating the deflection of the electret diaphragm 3 and the output voltage due to a sound pressure. Assuming piston-like movement of the conducting area

of the diaphragm 3, calculations indicate that higher open-circuit sensitivities are achievable.

Electret Microphone B

To reduce the stray capacitance between the electrodes and substrates and between the
5 two clamped silicon substrate halves of microphone A, a second electret microphone B
was fabricated. Fabrication of the microphone B membrane is the same as for microphone
A, but with a 1.2 μm thick electret layer implanted with 7 keV electrons. However,
microphone B uses a glass back plate. FIGURE 4 is a process flow chart showing
fabrication stages for the microphone B back plate.

- 10 1) The back plate of microphone B is fabricated starting with a glass substrate 10a
coated with a conductive layer 16 on one side, preferably about 2500 Å of Cr/Au.
Again other conductors could be used (although in the preferred embodiment, if
buffered hydrofluoric acid is used in the last stage etch, certain metals, such as Al
or Cu, should be avoided. This limitation can be avoided by using other etching
15 techniques). Further, the substrate 10a could be an electrically insulating ceramic,
crystalline, or polycrystalline material.
- 2) Portions of the conductive layer 16 were masked with patterned photoresist 17.
- 3) The exposed portions of the conductive layer 16 were then etched to form the
patterned back plate electrode 15a.
- 20 4) A spacer 18 was then formed, preferably by applying and patterning a photoresist
layer about 5 μm thick.
- 5) A cavity array 19 is then formed in the glass substrate 10a, preferably using a
timed buffered hydrofluoric acid (BHF) etch. These cavities serve to reduce the

air streaming resistance. In the illustrated embodiment, each cavity has about a 40 μm diameter opening and a half-dome shaped hole about 70 μm in diameter and about 15 μm deep.

5 The electret microphone B was tested in a B&K Type 4232 anechoic test chamber with built-in speaker and was calibrated against a B&K Type 4136 1/4 inch reference microphone. When microphone B was connected to an EG&G Model 113 Pre-amp and was excited by a sinusoidal input sound source, a clear undistorted sinusoidal output signal was observed. By applying a known input sound pressure level (SPL) from 200 Hz to 10 kHz, the frequency response of microphone B was obtained. The open circuit
10 sensitivity of microphone B was found to be on the order of 0.2 mV/Pa and the bandwidth is greater than 10 kHz. At 650 Hz, the lowest detectable sound pressure was 55 dB SPL (re. 20 μPa). The open circuit distortion limit was found to be above 125 dB SPL, the maximum output of the speaker. This translates into a dynamic range that is greater than 70 dB SPL. The performance characteristics of microphone B are comparable to other
15 microphones of similar size, and preliminary calculations suggest potentially higher sensitivities and wider dynamic range are achievable.

Packaging for microphone B was the same as for microphone A, as was the formation of limited area electrodes to reduce stray capacitance. The measured resonance frequency of the membrane was approximately 38 kHz.

20 The theoretical capacitance of microphone A was 4.9 pF with a 5 μm air gap, a 1.2 μm thick Teflon electret 6, and an electrode area of 3.14 mm^2 . Using a Hewlett Packard 4192 LF Impedance Analyzer, the measured capacitance of the completed microphone B package was about 5.2 pF. The close agreement between theoretical capacitance value and the experimental value can be attributed to the glass substrate, which practically
25 eliminates stray capacitance between the electrodes and substrate and between the two clamped halves of the microphone.

Pseudo-spark Electron Gun

A pseudo-spark electron gun was used for electron implantation into the thin PTFE dielectric film. FIGURE 5 is a diagram of a preferred back-lighted thyratron (BLT) charge pseudo-spark electron gun for making electret films in accordance with the present invention. The BLT structure comprises two electrode plates 50, 52 with a hollow-back cathode 54 and a hollow-back anode 56. In the illustrated embodiment, the two electrodes 50, 52 face each other and have a diameter of about 75 mm and a center aperture 58 of about 5 mm. The electrodes 50, 52 are separated by an insulating plate 60, such as plexiglass, quartz, *etc.*, about 5 mm thick. The structure is filled with a low pressure gas, such as hydrogen or one of the noble gases, to a pressure of about 50 to about 500 mTorr, maintained by a vacuum chamber 62 coupled to a pump (not shown). A high voltage power supply 64 provides an electric bias potential between the electrodes 50, 52.

The BLT device is triggered optically by an ultraviolet light pulse applied to the back of the cathode 54. That is, light from a UV source 66 (for example, a flashlamp) passes through a UV transparent window (*e.g.*, quartz) 68 into the back of the cathode 54. This initiates a pulsed electron beam 70 which is directed towards a thin film dielectric sample 72. Integrating a dielectric collimating tube 74 at the beam exit from the center aperture 58 has the effect of collimating and focusing the electron beam 72.

In an alternative embodiment, the thyratron device of FIGURE 5 may be triggered with an electrical pulse applied to the cathode region 54. The electrical pulse generates electrons which initiate the electron beam 70.

In one experimental setup, a BLT was constructed on top of a vacuum chamber 62 with a triggering UV flashlamp 66 at a distance of about 2 cm away from the UV transparent (quartz) window 68. The cathode 54 was biased at a high negative potential for beam acceleration. The electron beam pulse 70 was directed to the sample 72 positioned about 12 cm away from the beam exit from the center aperture 58. With a divergent angle of

about 6° , the beam diameter was about 1.75 cm at the sample surface. The bias potential was adjusted according to the desirable range of electrons in the dielectric sample 72. For microphone A, which has a silicon back plate and 1 μm thick Teflon film, the electron beam energy was set at 10 keV, which gives an implantation depth of approximately 1 μm . For microphone B, which has a glass back plate and 1.2 μm thick Teflon film, the electron beam energy was set at 7 keV, which gives an implantation depth of less than 1 μm .

Charge Density Measurements

To measure the charge density on the electrets, a setup consisting of a PZT stack and a micrometer controlled stationary electrode was constructed. To confine displacement in the z-direction only, the PZT was integrated into a flexure hinge made of 304 stainless steel and machined by electrical discharge machining (EDM). The movable part of the flexure hinge weighed 30 g and had a spring constant of 1.53×10^6 N/m. The PZT driver deforms 15 μm at 100 V and can be driven by a maximum voltage of 150 V. The linearity of the displacement of the PZT caused by hysteresis was 10%. The PZT was driven by a unit consisting of a periodic source and an amplifier. The amplifier was a class-B push-pull type amplifier specially designed for capacitive loads. An eddy-current sensor was integrated into the micrometer for monitoring and double checking dynamic and static displacements. A test sample was prepared using 1.2×1.2 cm silicon die evaporated with about 2000 Å of Cr/Au. A 1 μm thick layer of Teflon AF 1601S was coated on the Au surface and then implanted with 10 keV electrons using the BLT described above at 420 mTorr of helium.

The electret sample was fixed on top of the vibrating flexure hinge. The signal generated by induced charges on the stationary electrode due to the vibrating electret was then displayed on an oscilloscope. By applying a compensation potential, U_0 , between the two electrodes, the net electric field in the air gap between the vibrating and stationary electrode can be reduced to zero. The signal generated by the induced charges thus

becomes zero. The effective surface charge density, ρ_{em} of the electret sample is then given by:

$$\rho_{eff} = \epsilon_0 \epsilon U / t$$

5 where ϵ_0 is the permittivity of air, $\epsilon = 1.9$ is the relative permittivity of the Teflon film, and t is the electret thickness. Depending on the number of electron pulses, the charge density of an electret sample ranged from about 2×10^{-3} C/m² to about 8×10^{-4} C/m². The maximum charge density obtained is comparable to what has been reported for Teflon films.

10 It was found from experiment that at room temperature the electret initially undergoes a 10-20% drop in total charge density a few hours after implantation, but then stabilizes afterward. Some samples were monitored at room temperature over a period of six months and no detectable charge decay was observed. Samples have also been tested for charge decay at elevated temperatures in air. The charge density of a sample at 100°C dropped about 40% drop in the first 2 hours, due to the elevated temperature. However, even at 100°C the charge stabilized after the initial drop to a rate which is not measurable within 15 the time span of the experiment (16 hours). The same electret sample was then monitored for charge decay at 120°C. Again there was an initial drop in charge density, but the charge stabilized after a few hours. The same trend was observed for the same sample at 140°C, and for a different sample at 130°C and 160°C. It was also discovered that at 190°C the electret tested lost more than 80% of its charge within a few hours.

20 Using these thermal annealing data, a procedure was devised to stabilize the charge in an electret made in accordance with the invention by thermally annealing the electret in air at about 100°C for about 3 hours essentially immediately after charge implantation. After thermal annealing, the result is a stable electret at room temperature. When one such thermally annealed electret sample was exposed to UV light (365 nm at 3.85 mW/cm², 25 400 nm at 8.5 mW/cm²) for one hour, no charge decay was observed.

Although only short term data has been available so far, the charge decay data obtained at room and elevated temperatures and in the presence of UV light suggests that a stable electret can be formed using PTFE (particularly Teflon® AF) and the BLT.

Summary

5 The electret of the present invention can be used in any application where a conventional electret can be used. In particular, the electret microphone of the present invention can be used in any application where a conventional electret microphone can be used. In addition, because of its extremely small size and self-powering characteristics, an electret microphone made in accordance with the invention can contribute to further miniaturiza-
10 tion of devices such as portable telecommunications devices, hearing aids, *etc.* Moreover, such an electret microphone can be used as a powered sound generator, allowing one or more of the units to be used, for example, in a hearing aid as a speaker. If multiple microphones are used, the frequency response of each can be tuned to desired values by changing the stiffness of the diaphragm 3 (*e.g.*, by changing its thickness or in-plane residual stress) or by changing the area of the diaphragm 3.
15

Since the MEMS processes used in fabricating electrets and electret microphones in accordance with the present invention are compatible with fabrication of integrated circuitry, such devices as amplifiers, signal processors, filters, A/D converters, *etc.*, can be fabricated inexpensively as an integral part of the electret-based device. Further, the
20 low cost of manufacture and the ability to make multiple microphones on a substrate wafer permits use of multiple microphones in one unit, for redundancy or to provide directional sound perception.

The high charge density, thin film stable electret technology of the present invention can also be used in applications other than microphones, such as microspeakers, microgener-
25 ators, micromotors, microvalves, and airfilters.

A number of embodiments of the present invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, other etchants, metals, mask and substrate materials, lithographic methods, etching techniques, *etc.*, may be used in place of the specific materials and methods described above. Other dimensions for thicknesses, sizes, *etc.* can also be used to achieve desired performance or fabrication parameters. While square microphones are shown, other shapes, such as round, hexagonal, or ellipsoid, can also be fabricated. Further, some specific steps may be performed in a different order to achieve similar structures. Accordingly, it is to be understood that the invention is not to be limited by the specific illustrated embodiment, but only by the scope of the appended claims.

CLAIMS

What is claimed is:

- 1 1. A method of fabricating an electret by the step of forming, by micro-machining
2 techniques, an electret layer on a support structure.
- 1 2. The method of claim 1, further including the step of thermally annealing the
2 electret layer to stabilize charge therein.
- 1 3. The method of claim 2, wherein the step of thermally annealing comprises heating
2 the electret layer to about 100°C for about 3 hours.
- 1 4. The method of claim 1, wherein the support structure is formed from an
2 electrically insulating or semiconducting glass, ceramic, crystalline, or
3 polycrystalline material.
- 1 5. The method of claim 1, wherein the support structure comprises a membrane
2 fabricated to a thickness of about 1 μ m.
- 1 6. The method of claim 1, wherein the electret layer is formed by the steps of:
2 (a) applying a dielectric film on the support structure;
3 (b) implanting electrons into the dielectric film.
- 1 7. The method of claim 6, further including the step of implanting electrons into the
2 dielectric film by means of a pseudo-spark electron gun.
- 1 8. The method of claim 6, wherein the dielectric film is formed from one of Mylar,
2 FEP, a PTFE fluoropolymer, Teflon® AF, a silicone, or Parylene.

- 1 9. The method of claim 1, wherein the electret has a saturated charged density from
2 about 2×10^{-5} C/m² to about 8×10^{-4} C/m².
- 1 10. A method of fabricating an electret sound transducer by the steps of:
2 (a) forming, by micro-machining techniques, a transducer membrane having
3 a first electrode;
4 (b) forming, by micro-machining techniques, a transducer back plate having
5 a second electrode;
6 (c) forming an electret layer on at least one of the transducer membrane or the
7 transducer back plate;
8 (d) positioning the transducer membrane adjacent to the transducer back plate
9 to form an electret sound transducer.
- 1 11. The method of claim 10, further including the step of thermally annealing the
2 electret layer to stabilize charge therein.
- 1 12. The method of claim 11, wherein the step of thermally annealing comprises
2 heating the electret layer to about 100°C for about 3 hours.
- 1 13. The method of claim 10, wherein the transducer membrane is formed on a support
2 structure formed from an electrically insulating or semiconducting glass, ceramic,
3 crystalline, or polycrystalline material.
- 1 14. The method of claim 10, wherein the transducer back plate is formed from an
2 electrically insulating or semiconducting glass, ceramic, crystalline, or
3 polycrystalline material.
- 1 15. The method of claim 10, wherein the transducer membrane is fabricated to a
2 thickness of about 1 μ m.

- 1 16. The method of claim 10, wherein the electret layer is formed by the steps of:
2 (a) applying a dielectric film on at least one of the transducer membrane or
3 the transducer back plate;
4 (b) implanting electrons into the dielectric film.
- 1 17. The method of claim 16, further including the step of implanting electrons into the
2 dielectric film by means of a thyatron.
- 1 18. The method of claim 16, wherein the dielectric film is formed from one of Mylar,
2 FEP, a PTFE fluoropolymer, Teflon® AF, a silicone, or Parylene.
- 1 19. The method of claim 10, wherein the electret has a saturated charged density from
2 about 2×10^{-5} C/m² to about 8×10^{-4} C/m².
- 1 20. The method of claim 10, further including the step of:
2 (a) operating the electret sound transducer as a microphone, whereby ambient
3 sounds are transformed by the electret sound transducer into electrical
4 signals on the first electrode and the second electrode.
- 1 21. The method of claim 20, wherein the microphone has an open circuit sensitivity
2 of about 0.5 mV/Pa.
- 1 22. The method of claim 10, further including the steps of:
2 (a) operating the electret sound transducer as a speaker by applying electrical
3 signals through the first electrode and the second electrode so as to induce
4 physical motion of the membrane under the influence of the electret layer,
5 thereby generating sound waves.

- 1 23. An electret comprising:
2 (a) a support structure;
3 (b) an electret layer formed on the support structure by micro-machining
4 techniques.
- 1 24. The electret membrane of claim 23, wherein the electret layer is thermally
2 annealed to stabilize charge therein.
- 1 25. The electret membrane of claim 23, wherein the electret layer is heated to about
2 100°C for about 3 hours for thermal annealing.
- 1 26. The electret membrane of claim 23, wherein the support structure is formed from
2 an electrically insulating or semiconducting glass, ceramic, crystalline, or
3 polycrystalline material.
- 1 27. The electret membrane of claim 23, wherein the support structure comprises a
2 membrane about 1 μm thick.
- 1 28. The electret membrane of claim 23, wherein the electret layer comprises a charged
2 dielectric film formed on the support structure.
- 1 29. The electret membrane of claim 28, wherein the dielectric film is charged by
2 implanting electrons into the dielectric film by means of a thyatron.
- 1 30. The electret membrane of claim 28, wherein the dielectric film is formed from one
2 of Mylar, FEP, a PTFE fluoropolymer, Teflon® AF, a silicone, or Parylene.
- 1 31. The electret membrane of claim 23, wherein the electret has a saturated charged
2 density from about $2 \times 10^{-5} \text{ C/m}^2$ to about $8 \times 10^{-4} \text{ C/m}^2$.

- 1 32. An electret sound transducer comprising:
2 (a) a membrane support structure;
3 (b) a transducer membrane having a first electrode and formed on the
4 membrane support structure by micro-machining techniques;
5 (c) a transducer back plate having a second electrode and formed by micro-
6 machining techniques;
7 (d) an electret layer formed on at least one of the transducer membrane or the
8 transducer back plate;
9 the transducer membrane being positioned adjacent to the transducer back plate,
10 thereby forming the electret sound transducer.
- 1 33. The electret sound transducer of claim 32, wherein the electret layer is thermally
2 annealed to stabilize charge therein.
- 1 34. The electret sound transducer of claim 32, wherein the electret layer is heated to
2 about 100°C for about 3 hours for thermal annealing.
- 1 35. The electret sound transducer of claim 32, wherein the membrane support
2 structure is formed from an electrically insulating or semiconducting glass,
3 ceramic, crystalline, or polycrystalline material.
- 1 36. The electret sound transducer of claim 32, wherein the transducer back plate is
2 formed from an electrically insulating or semiconducting glass, ceramic,
3 crystalline, or polycrystalline material.
- 1 37. The electret sound transducer of claim 32, wherein the transducer membrane is
2 about 1 μm thick.

- 1 38. The electret sound transducer of claim 32, wherein the electret layer comprises a
2 charged dielectric film formed on the transducer membrane.
- 1 39. The electret sound transducer of claim 38, wherein the dielectric film is charged
2 by implanting electrons into the dielectric film by means of a thyratron.
- 1 40. The electret sound transducer of claim 38, wherein the dielectric film is formed
2 from one of Mylar, FEP, a PTFE fluoropolymer, Teflon® AF, a silicone, or
3 Parylene.
- 1 41. The electret sound transducer of claim 32, wherein the electret has a saturated
2 charged density from about 2×10^{-3} C/m² to about 8×10^{-4} C/m².
- 1 42. The electret sound transducer of claim 32, wherein the electret sound transducer
2 is operated as a microphone whereby ambient sounds are transformed by the
3 electret sound transducer into electrical signals on the first electrode and the
4 second electrode.
- 1 43. The electret sound transducer of claim 42, wherein the microphone has an open
2 circuit sensitivity of about 0.5 mV/Pa.
- 1 44. The electret sound transducer of claim 32, wherein the electret sound transducer
2 is operated as a speaker by applying electrical signals through the first electrode
3 and the second electrode so as to induce physical motion of the membrane under
4 the influence of the electret layer thereby generating sound waves.

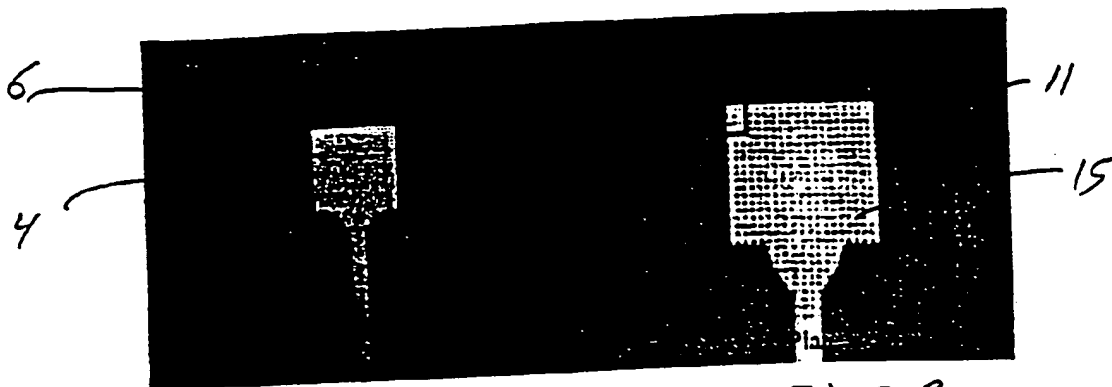


Fig. 2A

Fig. 2B

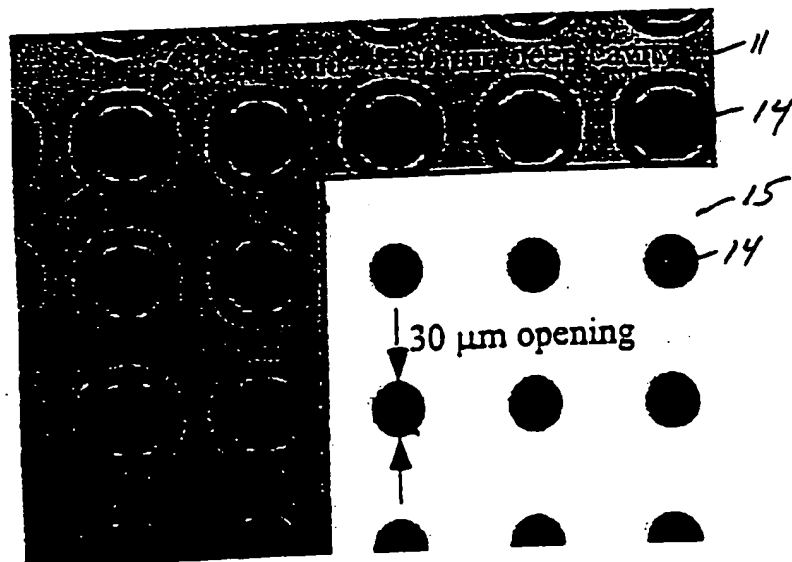


Fig. 2C

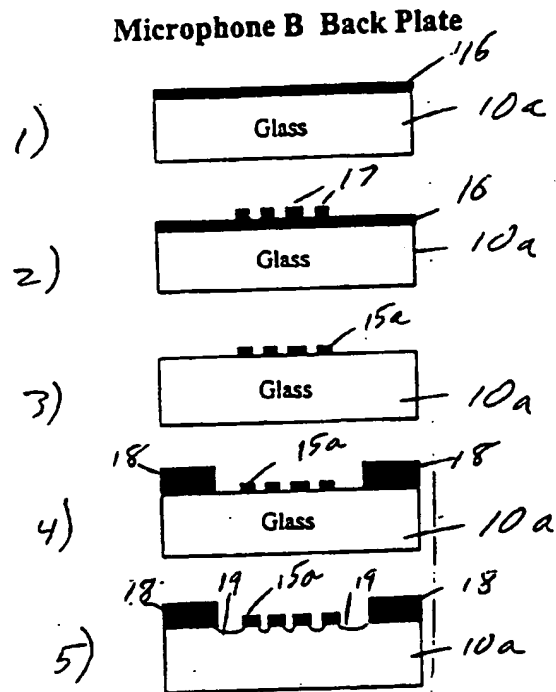
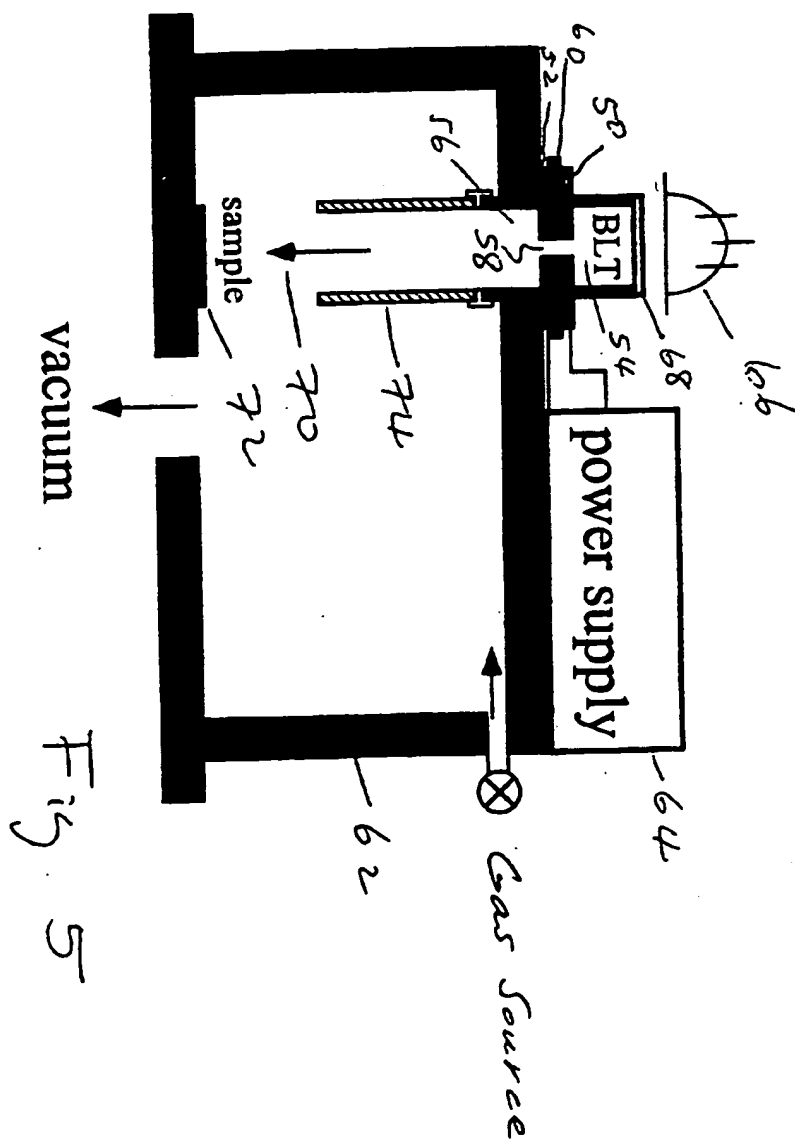


Fig. 4



INTERNATIONAL SEARCH REPORT

International application No.

PCT/US97/06554

A. CLASSIFICATION OF SUBJECT MATTER IPC(6) : H01G 7/02; H04R 31/00 US CL : 29/25.41, 594, 886; 307/400; 361/229, 233; 381/191 According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) U.S. : 29/25.35, 25.41, 592.1, 594, 886; 307/400; 361/229, 233; 381/191 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched None Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) APS		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 3,660,736 A (IGARASHI ET AL) 02 MAY 1972. See the entire reference.	1-4, 6, 8, 23-26 and 28 ----- 5, 7, 10-18, 20-22, 27, 29-30, 32-40 and 42-44
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document published on or after the international filing date "I" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reasons (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" documents published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "Z" document member of the same patent family		
Date of the actual completion of the international search 13 AUGUST 1997		Date of mailing of the international search report 05 SEP 1997
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230		Authorized officer PETER VO Telephone No. (703) 308-1789 <i>Sheila Vanez</i> <i>Paralegal Specialist</i> <i>Group 3200</i>

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/06554

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 3,924, 324 A (KODERA) 09 DECEMBER 1975. See the entire reference.	1-2, 4, 6, 8, 23, 24, 26, 28 ----- 3, 5, 7, 10-18, 20-22, 25, 27, 29-30, 32-40, 42-44
Y	US 4,429,192 A (BUSCH-VISHNIAC ET AL) 31 JANUARY 1984. See the entire reference.	5, 7, 10-18, 20-22, 27, 29-30, 32-40 and 42-44
A	US 4,524,247 A (LINDENBERGER ET AL) 18 JUNE 1985. See the entire reference.	1-44
A	US 4,764,690 A (MURPHY ET AL) 16 AUGUST 1988. See the entire reference.	1-44
A	US 4,910,840 (SPRENKELS ET AL) 27 MARCH 1990. See the entire reference.	1-44
A	US 5,408,731 (BERGGVIST ET AL) 25 APRIL 1995. See the entire reference.	1-44
A	CA 970,884 A (KODERA ET AL) 08 JULY 1975. See the entire reference.	1-44